Physics-of-Failure and the Improved Ribbon Bridge — Modeling and Simulation Ensure Program Success

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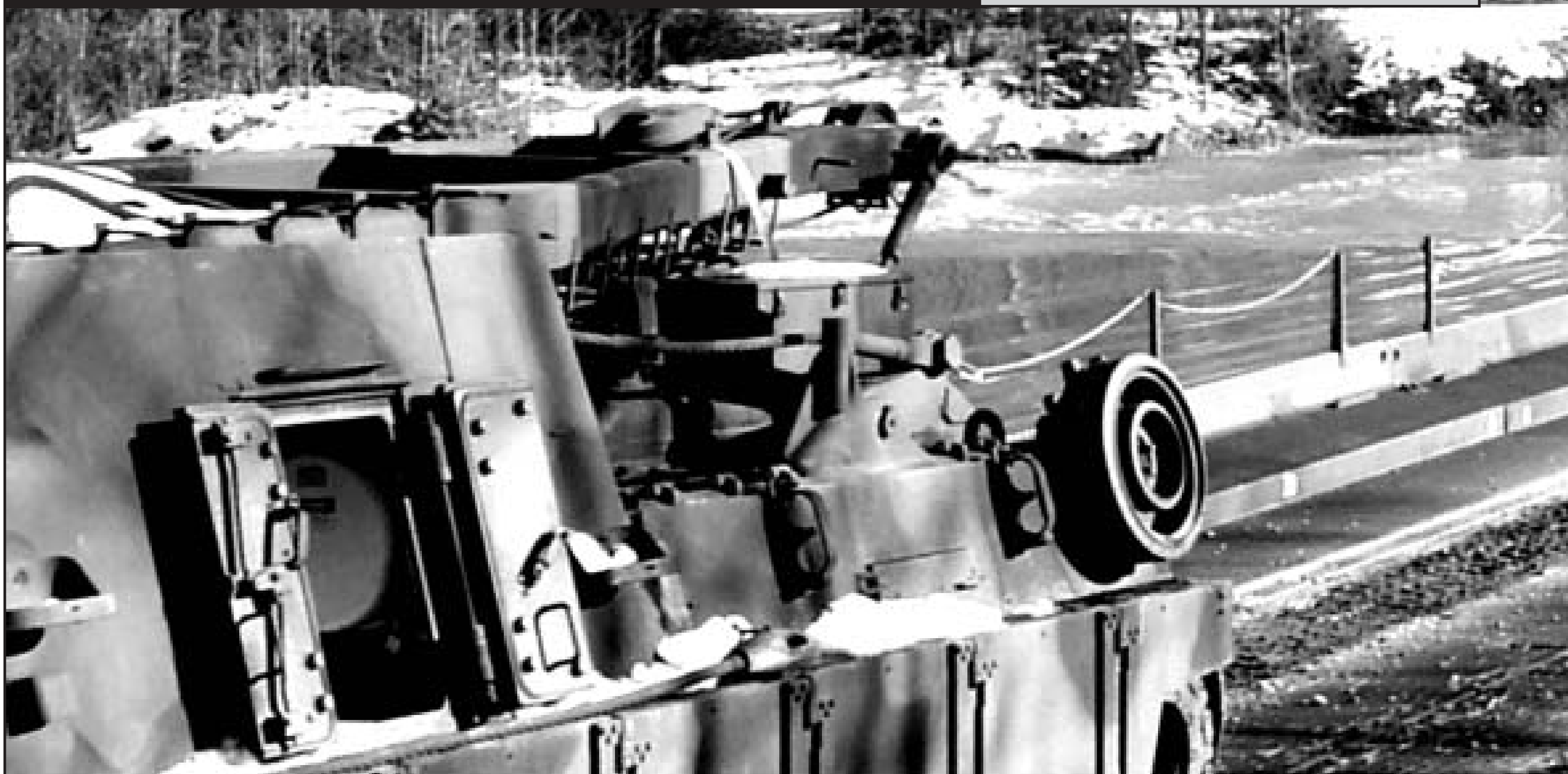

A physics-based computer-modeling analysis technique — Physics-of-Failure (PoF) — is used to identify the root causes of failures in mechanical and electronic systems. PoF modeling and simulation (M&S) recently enabled the Improved Ribbon Bridge (IRB) to meet a critical fielding suspense to support *Operation Iraqi Freedom (OIF)* and save an estimated $2 million in program costs. The IRB is a floating, modular system that can be used for bridging and rafting. The IRB aluminum modules can be connected together to form a continuously supported shore-to-shore roadway or connected to form rafts that can be used to ferry loads across water obstacles.

The Product Manager (PM) Bridging, located in the Program Management Office Force Projection (PMO FP) was responsible for developing, testing and fielding the new IRB. During the research, development and engineering process for bridging systems — one of the most costly and time-consuming tasks in bridge durability testing — extensive field trials can involve thousands of vehicular crossings, can take up to a year to conduct and cost more than $2 million. As part of the bridge development, IRB contractor General Dynamics Santa Barbara Sistemas GmbH planned to conduct fatigue life testing as partial design verification. During the tests, the critical IRB components would be load cycled in specially designed laboratory test apparatus to prove their durability. The IRB test and evaluation (T&E) community realized that significant savings could be achieved if the contractor test data could be used to replace some of the durability test's extensive field crossings. To accept the contractor test data, the Army Test and Evaluation Command would require that the laboratory test be viewed as M&S and that a sound verification, validation and accreditation (VV&A) effort be conducted to ensure that the load simulation was valid.

The PM formed an M&S integrated product team (IPT), and work on a Simulation and Support Plan (SSP)

This bridge was set up for the IRB Developmental Testing at Aberdeen Test Center, Aberdeen Proving Ground, MD.

This 572-foot floatbridge over the Tigris River near Baghdad is the longest built since WWII. It was built through the concerted efforts of three multi-role bridge companies: the 502nd, Hanau, GE; the 814th, Fort Polk, LA; and the 74th, Fort Hood, TX.

began. The U.S. Army Tank Automotive Research, Development and Engineering Center was tasked to perform the V&V activities and the U.S. Army Materiel Systems Analysis Activity (AMSAA) was selected as the accreditation agent responsible for performing the detailed accreditation analysis.

The durability test concept that emerged from the T&E and M&S IPTs relied on a combination of actual crossings and physical simulation (i.e., M&S) to gather the necessary data to address the bridge durability requirement.

The bridge designer predicted the dynamic forces that act on bridge components during crossings. Laboratory test apparatus were designed to apply the predicted loads to the selected components. Test apparatus included computer-controlled hydraulic actuators to apply the load and various fixtures to ensure that the application of the load on the component was similar or equivalent to that in an assembled bridge.

The V&V efforts focused on establishing the simulation's scientific merit and correlating the data with actual bridge crossing strains induced in the critical components. Unfortunately, because of the compressed development and testing schedules, the laboratory fatigue tests were conducted before the actual crossings. This sequence of events presented a degree of risk. Actual critical component stresses and strains would not be known until crossing tests were conducted. If the component loads (loads used as input for the simulation) were underpredicted by the bridge designer, the M&S effort might be an undertest and be rendered unacceptable. To help prevent the possibility of an undertest, the test durations were extended. If the loads applied in the simulation undertested the components, then the additional cycles would compensate. However, in the case of a severe undertest, the additional cycles might not be sufficient to induce the necessary total fatigue to ensure M&S validity.

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To mitigate this risk, a backup plan was developed that would implement PoF analysis methods if the M&S proved inconclusive. The accuracy of PoF modeling tools can be increased when used in conjunction with measured data to formulate life predictions of components undergoing cyclic loading such as bridge crossings.

The strains that were induced in the critical components during the M&S were compared to the strains that occurred during actual vehicle crossings. Most strain comparisons were favorable, with the exception of the bridge lower lock component. The lower lock device serves to hold the bridge modules together during operations. The failure of this component during operations could have catastrophic consequences. The degree of undertest was significant and even the additional cycles conducted were insufficient to compensate. A detailed PoF analysis was initiated to determine the robustness of the lower lock design.

For the PoF analysis to be acceptable to the T&E community, it would need to meet a high standard of conservatism. Furthermore, if the analysis did not reveal that the lower lock component was capable of meeting the IRB durability requirement, an expensive redesign and component retest would be required. It was estimated that this scenario could delay the program 1 year and cost more than $2 million. The PoF approach, being a form of M&S, would also require VV&A. These responsibilities were assigned to the U.S. Army Aberdeen Test Center, Aberdeen Proving Ground, MD.

The PoF analysis used finite element modeling (FEM) of the lower lock component and the dynamic strain data that were collected from the component during bridge crossings. Combining the FEM with actual measured data provided detailed information about the peak strains that were induced at the potential crack initiation location within the component.

To predict fatigue life using PoF tools, it is necessary to know the induced strain magnitude, strain range, mean strain, number of applied strain cycles and the material properties. The component material properties were available from the contractor. The strain

magnitude, range, mean and number of cycles for each crossing could be determined from the FEM and field crossing data. The data were compiled using special PoF fatigue life prediction software to determine the likelihood of component failure during service life.

The most conservative life prediction technique is the stress-life fatigue analysis approach. This methodology uses analytical techniques to relate the strain cycles occurring in the component to the known fatigue data for the particular material and the manufacturing process used to form the component (e.g., heat treatment, cast, forged, etc.).

Fatigue data are available in Wohler S-N diagrams where stress (S) is plotted against the number of stress cycles (N). The stress-life analysis prediction for the component was 31,400 Military Load Class (MLC) 70 crossing cycles. An MLC 70 crossing is approximately


Combat engineers move an IRB into place on the Tigris River during *OIF*.

equivalent to a 70-ton tracked vehicle crossing the bridge. The durability requirement for the IRB is 12,344 MLC 70 crossings. Since the predicted life of 31,400 MLC 70 crossings is significantly larger than the 12,344-threshold requirement, it would seem that the component possesses ample durability. However, the Wohler S-N based 31,400 MLC 70 crossing prediction indicates 50-percent survival. Fatigue data has associated with it significant scatter. To be certain that the weakest bridge produced will still meet the user requirements, it is necessary to estimate the statistical spread of the data corresponding to the life prediction. This determines if any portion of the fielded bridge population might experience failures before the durability requirement is reached.

To accomplish this, a standard deviation that would correspond to the lower lock fatigue life population is assumed. Making an assumption about the value of a standard deviation might appear to introduce risk. However, for evaluation purposes, it is only necessary to estimate a standard deviation that would be greater than the actual component's standard deviation. A standard deviation overestimate would increase the apparent data scatter and result in conservative life predictions. The estimate is made by referring to published fatigue life data for various structural components. In this case, the European Convention for Construction Steelwork fatigue guide for steel and aluminum structures was used to estimate the standard deviation. The maximum value presented was selected to ensure conservatism. Incorporating the standard deviation estimation gives a probabilistic context to the life prediction. The results show that 100 percent of the bridges can be expected to meet the user's 12,344 MLC 70 requirement and that the first failures of the weakest bridges will not occur until more than 20,000 MLC 70 crossings have occurred.

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The PoF assessment's convincing nature was sufficient to avoid the need for a retest. An urgent IRB materiel release in support of *OIF* was executed with the assurance that bridge durability was not in question. The direct cost avoidance of the retest was estimated at approximately $1 million, with an additional $1 million attributed to the indirect costs that a program delay would have incurred. This example shows how the prudent use of PoF M&S technology can ensure program success while reducing program risk and costs.

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